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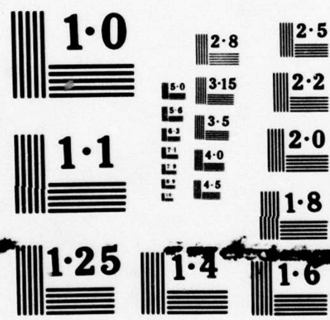

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TECHNICAL INFORMATION BULLETIN
78-1

EMP, LIGHTNING AND POWER TRANSIENTS: THEIR THREAT AND RELEVANCE TO EMP PROTECTION STANDARDS FOR TELECOMMUNICATION FACILITIES

AUGUST 1978

(9) NCS TECHNICAL INFORMATION BULLETIN 78-1

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EMP, LIGHTNING, AND POWER TRANSIENTS: THEIR THREAT AND RELEVANCE TO EMP PROTECTION STANDARDS FOR TELECOMMUNICATION FACILITIES.

(11) Aug[redacted]78

(12) 38 p.

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FOREWORD

It is generally recognized that telecommunication systems are vulnerable to upset or disablement from the effects of high energy electromagnetic pulse (EMP) which is a phenomenon of high altitude nuclear explosions. It is also recognized that many of the engineering, installation, and maintenance practices used to protect telecommunication systems from lightning and power surges, while helpful, fall short of offering assured protection against EMP. The Manager, National Communications System (NCS) is responsible for the development of standards and practices to improve the survivability and utility of Federal telecommunication resources during national emergencies. Accordingly, the NCS has initiated a three phase program to develop Federal standards for the protection of government owned and leased telecommunication facilities and services from disabling damage by EMP. This Technical Information Bulletin (78-1) (based on studies conducted for the NCS by the Defense Communications Engineering Center) presents the results of the Phase I effort. It is aimed at identifying and analyzing the similarities and differences of the spectral and energy content of lightning (direct strokes and induced), power surges, and EMP and identifying in a general way the shortcomings of lightning and surge protection measures against the EMP threat. Phases II and III will analyze the vulnerability of specific general categories of telecommunication facilities to EMP and identify remedial emergency and maintenance practices which can be codified in a series of Federal Standards. Comments concerning this TIB are welcome and should be addressed to:

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National Communications System
ATTN: NCS-TS
Washington, D.C. 20305

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SUMMARY

The electromagnetic pulse (EMP) is a phenomena created by nuclear explosions. It is a transient electromagnetic wave produced by exoatmospheric, atmospheric, and surface bursts and is characterized chiefly by its short duration, high intensity field. This electromagnetic field can cause severe disruption and possible damage to communications equipment. The most serious EMP threat is that from an exoatmospheric or high altitude burst which potentially can illuminate a large fraction of a communications network and simultaneously disrupt or damage communication equipment over a wide geographical user service area. It is EMP from the high altitude burst that is emphasized in this document since the EMP, blast, radiation, and thermal effects of atmospheric and surface bursts are only significant in negating geographically small communication functions.

A general physical understanding of the EMP phenomena as generated by the high altitude burst is presented to emphasize the transient radiated field characteristic of the EMP. This discussion is followed by a description of the radiated field characteristics. These include the magnitude, time history, and polarization of the field and its variations over the earth's surface as a function of height of weapon burst and observer location. A generalized characterization of the EMP radiated field is provided that represents the worst case for all the parameters.

The worst-case energy magnitudes coupled to the equipment connections by facility cables from this EMP field are discussed next to illustrate the complex and significant role of the intrasite and penetrator cables. References are provided which can be used to determine this EMP field coupling to cables and the magnitude of the energy and voltage surges. Data, data sources and examples are provided which compare measured data to these worst-case coupled energy values. The potential EMP threat is developed from these worst-case energy estimates by comparing them to the published failure thresholds of electronic components. The uncertainty of these energy coupling and failure threshold estimates is underscored.

Lightning and Power line energy surges are discussed ~~in Sections III and IV~~. The published surge characteristics for the time domain are provided and the energy threat defined for equipment connected to cable conductor interfaces. Worst-case energy values are provided for comparison to the EMP worst-case energy values of Section II. Surge specifications for stress testing equipment interfaces that connect to signal and power cable conductors are discussed for both the lightning and power cases. It is emphasized that the power surge energy presented to equipment interfaces is somewhat greater than expected and is an inadequately defined environment in the engineering reliability sense.

Section V organizes the data from the preceding sections on EMP, lightning and power energy surge characteristics. The similarities and differences between the three surge environments and the existing surge test standards are highlighted.

The material presented has been adapted from the listed references and was selected to focus the most recent data on the problem of developing standards for EMP protection. The material is not complete or comprehensive but is intended to uncover the only slightly explored area of compatibility between the various surge tests and expected EMP surges.

I. INTRODUCTION

This document is one of a series concerning Electromagnetic Pulse (EMP) effects on communications and computer systems, both analog and digital. It is based upon Technical Note (TN) 22-77, which was prepared by the Defense Communications Engineering Center in response to tasking received from the Manager, National Communications System. The purpose of the series is to provide information to system managers on EMP effects and the vulnerability of existing communications assets. The vulnerability effects considered in the series will include damage only aspects which excludes operational upsets such as false alarms or computer errors that can be corrected by system personnel.

This first report deals with the characteristics of the High Altitude Electromagnetic Pulse (HEMP) and its hazard to communications, computer, and control facilities and their associated peripherals, including their interconnection to land line facilities (cable, microwave, and power). The objective is to present pertinent EMP engineering data that describes and quantifies this hazard to equipment and plant, including appropriate comparisons to the normal environmental hazards of lightning and power line transients. This comparison is important in focusing the reader's attention on some important facts. The energy delivered to facility equipment by an average lightning stroke exceeds that of the EMP worst-case pulse. The energy of most transients, lightning stroke, power line fault/inrush currents and the EMP pulse exceed the damage thresholds of the most sensitive electronic components, i.e., the semiconductors. Existing surge test standards for lightning and power line transients already provide considerable EMP protection, since they exceed the energy expected from EMP signals at some equipment interfaces.

Some modifications to these surge test standards may be necessary to ultimately provide a final specification that covers the full arena of transient protection for the totality of communications,computer, and power equipment used in typical DCS or commercial facilities.

It is hoped that the protection philosophy and data provided in this report will be expanded by additional statistical effort and verified by other EMP researchers to ultimately permit a conclusive and comprehensive specification for application to transient protection problems. Comments and suggestions to assist in achieving this goal are welcome.

II. EMP PHENOMENA: RADIATED FIELD CHARACTERISTICS AND HAZARD FOR THE HIGH ALTITUDE BURST

1. INTRODUCTION

The electromagnetic pulse (EMP) is a phenomena created by nuclear explosions. It is a transient electromagnetic wave produced by exatmospheric, atmospheric, and surface bursts and is characterized chiefly by its short duration, high intensity electromagnetic field. This electromagnetic field can cause severe disruption and possible damage to communications equipment. The most serious EMP threat is that from an exoatmospheric or high altitude burst which potentially can illuminate a large fraction of a communications network and simultaneously disrupt and damage communications equipment over a wide geographical user service area. It is EMP from the high altitude burst that is emphasized in this document since the EMP, blast, radiation, and thermal effects of air and surface bursts are only significant in negating geographically small communications functions. At distances where EMP effects dominate over other nuclear effects the high altitude burst EMP is nearly always a worst-case situation.

A general physical understanding of the EMP phenomena as generated by the high altitude burst is provided to the reader to emphasize the transient nature of the EMP radiated field. This discussion is followed by a description of its radiated field characteristics. These include the magnitude, time history, and polarization of the field and its variations over the earth's surface as a function of height of weapon burst and observer location. A generalized working characterization of the EMP radiated field is provided that represents the composite of extremes, or worst on worst-case, for all the parameters discussed; i.e., the shortest rise time, the longest fall time, and the maximum amplitudes for both vertical and horizontal polarization. Both time and frequency domain characterizations of this composite EMP radiated field are provided, as well as the energy curves.

The conversion of this EMP radiated field to a voltage/energy surge threat at the equipment terminals is discussed next. Typical surge values are provided from the various references and compared to equipment failure thresholds to derive a tentative and preliminary upper limit estimate of the EMP threat in terms of energy and voltage. It is pointed out that the equipment failure thresholds for energy and voltage surges are essentially independent of the surge source and are essentially invariant.

2. EMP GENERATION MECHANISM FOR THE HIGH ALTITUDE BURST

The high altitude nuclear burst occurs above the earth's atmosphere (40 kilometers or greater) and generates a radiated EMP field. The field is created by two primary mechanisms. The first is electron scattering which occurs when gamma rays from the nuclear burst collide with molecules in the surrounding

atmosphere. These collisions, called Compton Collisions, cause electrons to be separated from these molecules which, in turn, move rapidly away from the center of the burst, leaving behind the slower moving positive ions, as shown in Figure 1. This initial process of large-scale charge separation creates a strong, electric field. The second mechanism necessary to complete the generation of the radiated EMP field from this charge separation process is the interaction of these Compton electrons with the earth's geomagnetic field. This interaction process is most easily understood by considering the movement of the charges as a current (Compton current) which is influenced by the static flux lines of a magnetic field. The Compton electrons of this current are forced to spiral around these flux lines, accelerating in the process, and thereby radiating an electromagnetic field. This two-phase process, charge separation and electron interaction with the earth's magnetic field is shown in Figure 1. Also shown in the figure is a representation of the charge separation or source region, which physically is a pancake-shaped area of time and spatially varying air conductivity. This source region is also called the deposition region and is the space around the burst that contains a highly conducting plasma with a radius of about 3,000 km.

References [1,6] provide additional descriptive and quantitative data for the EMP phenomena of the high altitude burst. For example, the gamma rays initiating the Compton process are nearly completely absorbed when the rays reach an altitude of 20 km, while above 40 km the atmosphere is not very dense and Compton scattering effects are minimal. This, then, places the pancake-shaped source region between these two limits of 20 to 40 km. The geomagnetic turning effect on the Compton electrons provides a turn radius of about 100m (the maximum distance before reabsorption), which produces large currents in nonradial directions from the burst, i.e., transverse. It is this transverse current that models into a phased magnetic dipole array that is the primary source of the high altitude radiated EMP. This dipole model translates these physical mechanisms into the radiated field characteristics that are familiar to the electrical engineer and the communications manager. These radiated field characteristics include spatial extent, time waveform, peak amplitude, polarization, and spectral energy content.

a. Geographical Coverage. The maximum EMP radiated fields from a number of high altitude bursts can be a significant threat to telecommunications since their combined range or coverage over the earth's surface can illuminate major portions of the communications network between many sets of users, including many possible alternate routes.

Figure 2 is a plot of the surface area coverage and the tangent radius (distance covered on the earth's surface from directly beneath the burst point to the tangent point at the horizon) as a function of height of burst (HOB).

Figure 3 is the same data overlaid on a United States map for three values of HOB. A short study will verify that the 300 HOB circle in the figure covers most of the United States (a surface area of about 3 million square miles and a tangent radius distance of about 1,500 km).

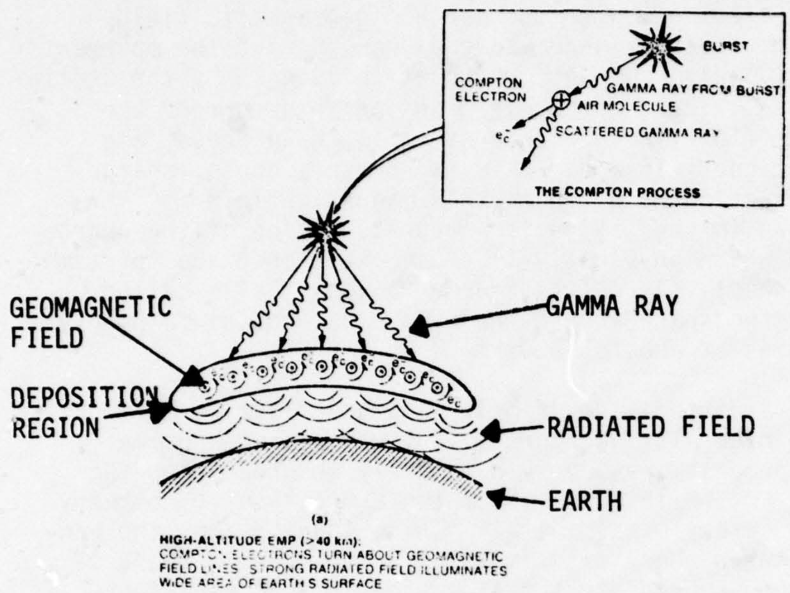


Figure 1. Mechanisms of High Altitude EMP Generation [2]

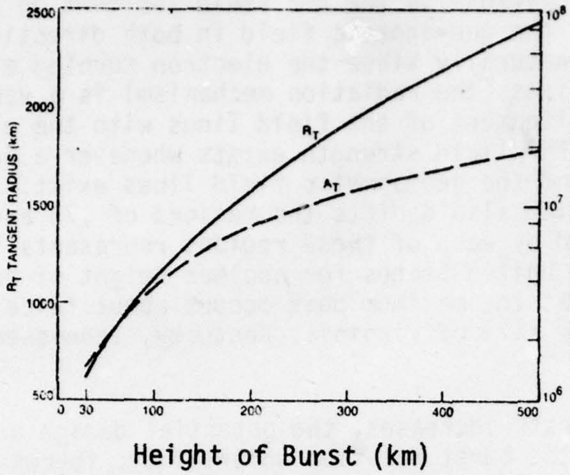


Figure 2. EMP Ground Coverage (Tangent radius) and Total Area of Coverage as Functions of Height of Burst [2]

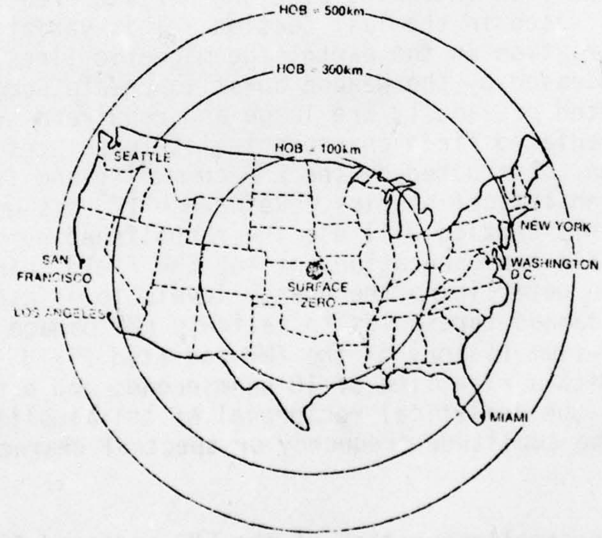


Figure 3. EMP Ground Coverage for High-Altitude Bursts at 100,300 and 500 km [2]

b. Geographical Variation of Field Strength. As explained previously, the EMP radiated field is generated by the interaction of the Compton electrons with the magnetic lines of the earth's geomagnetic field. It is reasonable, therefore, to expect variations in the EMP field incident on the earth's surface to follow those of the geomagnetic field in both direction and dip angle. These variations arise naturally since the electron turning effect caused by the geomagnetic field lines (the radiation mechanism) is a variable that depends on the relative alignment of the field lines with the electrons. In fact, a null region of EMP field strength exists whenever a parallel alignment between the electrons and the geomagnetic field lines exist. This null region is shown in Figure 4 which also depicts the regions of .75 and .5 of maximum field. The area covered by each of these regions represents the typical situations expected for the United States for nuclear height of bursts (HOB) from 100 to 500 km. Note that the maximum peak occurs about twice the HOB and covers an area about the size of Virginia, Kentucky, Tennessee, and North Carolina combined.

As the number of bursts increases, the potential damage area widens quickly and this, coupled with the burst location uncertainty, forces a more generalized specification of the EMP threat. This generalization has been accomplished by applying the worst-case specification of the E maximum region of Figure 4 to all other regions in the figure. This worst-case generalization of the EMP field is discussed more fully in the next section.

c. Energy, Amplitude, Time, and Spectral Properties. The EMP radiated field varies considerably in intensity over the surface area covered by the nuclear burst, as discussed in the last section. This variation stems primarily from the variation in the earth's geomagnetic lines, which interact with the electrons released by the weapon burst to create Compton currents. The variations, as noted previously, are large and require a worst-case specification of the EMP radiated field characteristics to be useful. Such a specification has been constructed by the EMP community and is widely accepted for experimental and analytical studies. Reference [2] has documented these characteristics and this section will use their published numerical values (see [1] also). Two specific representations of the EMP field characteristics are of great importance in determining the energy levels to be used for comparisons of telecommunication damage thresholds to validate EMP damage threats. These are (1) the amplitude-time history of the EMP radiated field (e.g., a 50,000 V/m amplitude pulse with a rise time of 10 nanoseconds and a duration of 200 nanoseconds); and (2) the analytical reciprocal of this amplitude-time history relationship, i.e., the amplitude-frequency or spectral characteristics of the EMP radiated field.

The generalized spectral properties of the EMP radiated field are shown in Figure 5. The electric field spectrum is shown as a solid line. The initial slope decreases at a frequency of 630kHz (the first breakpoint) at a rate of 20dB per decade. The second breakpoint occurs at a frequency of 76 MHz and decreases at a 40dB rate. The amplitude decrement, as shown, is sufficiently rapid to dismiss the influence of spectral energy beyond 100 MHz. (The magnetic field of the EMP is related to the electric field by a constant, the free space impedance).

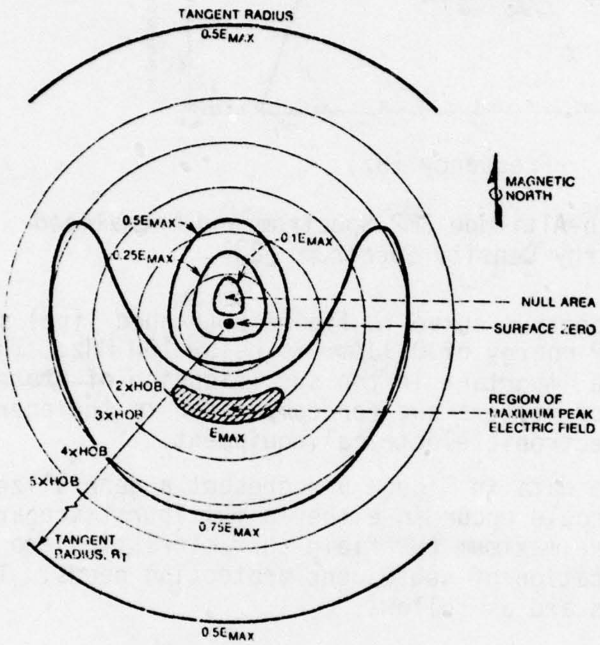


Figure 4. Possible Variations in High-Altitude EMP Peak Electric Field on Surface of Continental United States [2]

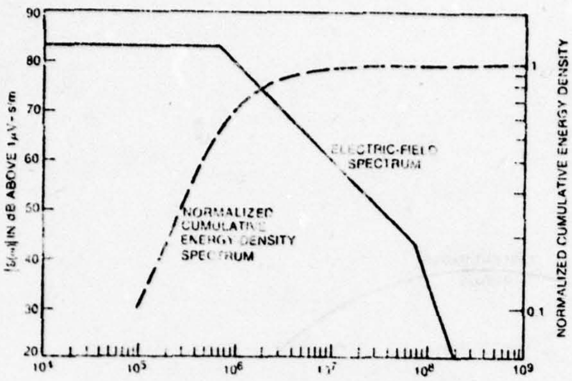


Figure 5. High-Altitude EMP Spectrum and Normalized Energy Density Spectrum [2]

The energy density spectrum curve in Figure 5 (dashed line) shows that over 99% of the total EMP energy of $0.9 J/m^2$ is below 100 MHz. These spectral and energy properties are important in the specification of protection components such as shields or filters and for comparison to the energy-spectral failure thresholds of electronic/electrical equipment.

Bear in mind that the data in Figure 5 represent a generalized worst-case EMP radiated field that could occur in either a multiburst scenario or in a worst-case situation where maximum EMP field characteristics are required for analysis and the specification of subsequent protection needs. The mathematical relations for these plots are as follows:

Spectrum: $$E(\omega) = \frac{2.47 \times 10^{13}}{(j\omega + 4 \times 10^6)(j\omega + 4.76 \times 10^8)}$$

Energy Density: $$S(\omega) = \frac{|E(\omega)|^2}{377}$$

ω = radian frequency

$E(\omega)$ = volt-seconds per meter

$S(\omega)$ = joules per square meter per hertz

Figure 6 is a plot of a worst-case generalized time function (waveform of the EMP field strength as a function of time).

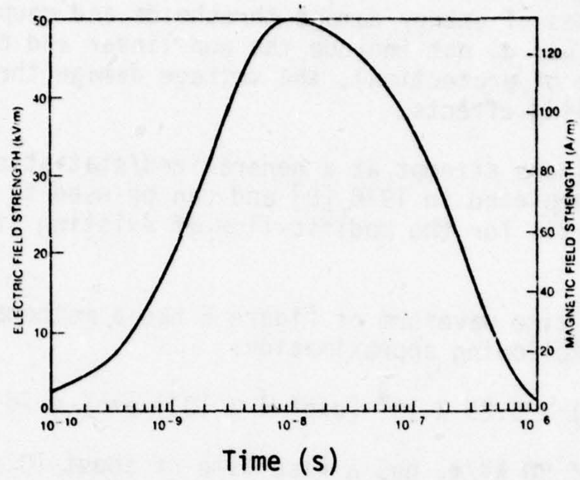


Figure 6. Generalized High-Altitude EMP Electric- and Magnetic-Field Time Waveform [2]

A characteristic of the EMP time function of importance is its amplitude rate of change for both the rise time and fall time; e.g., the generalized waveform has a rise time of 10 ns or 5,000 V/m/ns in Figure 6. This rise time characteristic is related to the high frequency portion of the spectral plot of Figure 5 and is responsible for the second breakpoint on that curve. The first frequency breakpoint is directly related to the half-width duration. The rates of change for EMP amplitude are important because they add a significant complication to the damage analysis problem, that of voltage breakdown and high frequency coupling. The first effect can be visualized by thinking of the cables in a system as having an induced voltage per unit length due to the conductor's inductance, and when the voltage between a pair of wires is sufficiently high, either a breakdown in air can occur (an arc) or the material between the wires can fail due to insulation breakdown. Essentially, the faster the rise time the greater the surge voltage (typically about 10-30 volts per inch of length on an analytical basis, Ldi/dt). In either event, the cable lengths and inductance values, as well as distances between possible arc points and impedances between wires, would have to be measured or determined from statistical inference before the EMP threat can be determined. Once these properties are known, as with the energy case considered in the last paragraph, the computed voltage can be compared to the voltage damage thresholds of the equipment components and cables. The second effect, high frequency coupling,can possibly produce damage effects at unpredictable locations in equipment circuitry and is a result of the impulse effect of the EMP field which forces a system cable response between 500 kHz and 20 MHz which then is mutually coupled to nearby cables/components.

Inherent in these discussions are the assumptions (1) that the coupling, parameters of cables/conductors are measured or available,perhaps in statistical form, (2) that both the energy and voltage damage thresholds are measured or known, and (3) that the coupling can be calculated with a reasonable degree

of accuracy. The reader should be aware that the research, to date, has been very limited in the general case or statistical arena, and comparisons/calculations are only estimates of energy damage thresholds and coupling parameters. Additionally, they do not include the non-linear and often mitigating effect of arcing (a form of protection), the voltage damage thresholds, and the high frequency coupling effects.

A useful and preliminary attempt at a generalized/statistical representation and analysis was completed in 1976 [8] and can be used to form an initial and partial technical basis for the modification of existing standards or specifications for EMP.

The generalized EMP time waveform of Figure 6 has a mathematical representation given by the following approximation:

$$E(t) = 5.25 \times 10^4 \, [\exp(-4 \times 10^6)-\exp(-4.76 \times 10^8)].$$

The peak of the pulse if 50 kV/m, has a rise time of about 10 ns, and a time to half-value of about 200 ns. These times represent the spread in values expected for the geographical coverage; e.g., (1) 50 ns in the maximum region and 200 ns at the tangent radius for half-values, and (2) rise times of 10 ns at the maximum region (see Figure 4).

d. <u>Polarization Properties</u>. The EMP radiated field polarization is a factor in determining/validating the EMP threat since it enters into the energy coupling calculations. The net result of the polarization properties is that a worst-case EMP radiated field threat is considered as being composed of two parts: (1) a horizontal polarized field and (2) a vertical polarized component. The polarization-magnitude variation actually depends on the geomagnetic field and the observer - burst geometry and has been computed and plotted for use in coupling calculations [1,2,7].

3. EMP RADIATED FIELD COUPLING TO TELECOMMUNICATIONS EQUIPMENT

The EMP field characteristics described in the last section are necessary but not sufficient to specify the threat to telecommunications equipment. The direct damage threat is not produced by the EMP field itself but by the response of the facility cables or conductors to the field which essentially converts the field to a voltage or current that appears at the equipment power and signal connections. This conversion is a complex phenomena that depends on the length of conductors attached to the equipment connections, the various conductors distance from nearby ground planes and each other, the conductors orientations to the EMP field and to each other, the conductor groupings and their shielding, the grounding of the shielding, and the impedances of the conductors and shields to each other and to ground. Reference [9] provides the appropriate analytical tools for many aspects of this conversion process and its calculation.

The direct threat to the equipment, therefore, is the energy that is provided by these resultant voltage and current surges at the equipment components located at these cable or conductor terminations. The extent of the threat, of course, depends on the magnitude and spectrum of this coupled energy and the failure levels or thresholds for the equipment components. Extensive analytical and experimental efforts have been made to characterize the worst-case coupling situations and the failure thresholds of components. These efforts have been partially successful and are reported in references [2,7,10-13]. The key point, at least from a standards development viewpoint, is that the threat is based on the energy content of the voltage and current surges that appear directly at the equipment interfaces that connect with the cables/conductors routed from the various equipments, whether they are power, signal, ground or shield conductors.

The magnitude of this threat is more easily understood by separating the facility cables/conductors into distinct physical groupings, and tabulating the worst-case coupled voltages/current data for each group and then comparing each of the energy magnitudes to the equipment component energy failure levels. The simplest cable groups or categories are (1) penetrator cables and (2) intrasite cables.

A penetrator cable is defined as one that enters/exits the building and is exposed to the EMP field exterior to the building. This class of conductors includes commerical power lines, facility grounds, waveguides and towers. Reference [2] cites worst-case EMP coupled current of 3000 amperes peak. Reference [14-16] derived an analytically possible range of energy values for penetrators that varies from a low of .18 joules to a maximum of 2.0 joules for a spectral range of 100 kHz to 5 MHz. (This is the energy at the interface of the building wall and the cable/conductor). Test data from references [7,10-13] appears to validate that the worst-case bound cited above is adequate as a starting point for the development of penetrator EMP standards. (Reference [9] provides another analytical development approach for simple cases.)

Intrasite cables are defined as those located entirely within the building and are used to interconnect power and signal lines among the various equipments and racks. Reference [2] provides a worst-case value for the intrasite cable case that range from a low of 0.5 amperes to a high of 12.0 amperes peak at energy levels of about 10 millijoules (100 ohms) for a spectral range from one to 20 MHz. Reference [14] developed a signal line equipment interface EMP specification of 5.8 amperes peak and 1300 volts for a special case situation which indicates that the worst-case estimates appear to bound actual specification cases developed from engineering data. References [10-13] provide test data from three different tests at AUTOVON sites for intrasite cables which indicate energy values and current magnitudes that are below this worst-case range stated above. The consensus of experimental and analytical results appears to indicate that the worst-case bound is adequate as a starting point for standards development for the intrasite case as in the penetrator cable case.

The two cable categories described above are useful because of the large differences in energy magnitudes between the two cases. A third cable energy coupling case, however, provides potential for damage to equipment components that exceeds the intrasite cabling case. This is the mutual coupled case where a penetrator cable couples energy to an intrasite cable. The only condition required is that the penetrator cable(s) be in proximity to the intrasite cable and follow parallel routes for a short distance. References [2,7,10-13] provide some limited data on this coupling magnitude and was given in terms of coupling loss. The maximum worst value expected for special cases from reference [2] was 60 amperes peak which can be extrapolated to an energy value of about 200 millijoules (100 ohms) at a 1 MHz ringing frequency. References[10-13] appear to substantiate this worst case limit but additional studies would be mandatory to assure that this limit would never be exceeded.

In summary, the worst-case EMP energy magnitudes for these three cases that appear at equipment terminal connections to cables is 2.0 joules for penetrators, 200 millijoules for intrasite cables coupled to penetrators, and 10 millijoules for intrasite cable terminations by themselves. The voltage and current magnitudes will depend on the cable impedances (a range from about 5 to 400 ohms). The spectral range from reference [2] is about 100 kHz to 20 MHz. On a practical basis, these coupling modes to cables and their translation to energy magnitudes at equipment connections is extremely complex and has large uncertainties. In the final analysis a validation step that involves tests and possibly a statistical approach,such as used by reference [8], appears essential before any consistent EMP standards development program or hardening program is initiated on a wide scale using worst-case energy estimates.

4. THE EMP THREAT AS A FUNCTION OF COMPONENT ENERGY FAILURE THRESHOLDS

Table I from references [5,6] provides a list of typical energy failure levels for equipment components and compares these levels to those expected for EMP from the intrasite and penetrator coupling described in the last section. The data in this table shows that the worst-case EMP energy exceeds the component failure thresholds by atleast one order of magnitude for the test conditions used to determine the component failure levels. In practice, these components are connected in multiple arrangements and each component lead may have many frequency selective shunt paths and the actual failure level may be much greater than the table indicates. Independent of this judgmental factor, however, a starting point for standard development can be formulated from this data. One possibility is to specify that the EMP penetration energy be reduced by a factor of about 1000 and that EMP intrasite energy be reduced by a factor of 100. A second possibility is that the equipment be required to withstand the full worst-case energy of either 200 mJ or 2.0J depending on whether the equipment is connected to penetrators or intrasite cables.

TABLE I. COMPONENT FAILURE LEVELS

Component	Component Failure Level in Joules	EMP Energy - Joules
Semiconductor & Integrated Circuits	10×10^{-6} to 1×10^{-3}	.010 - .20 *
Resistor (1/4 watt)	10×10^{-3}	.010 - .20 *
Capacitor	60×10^{-6} to 3.3×10^{-3}	.010 - .20 *
Relay	2×10^{-3} to 100×10^{-3}	.20 - 2.0 +

*Intrasite Interface
+Penetration Interface

In summary, the available references indicate some uncertainty in the actual EMP threat to telecommunications that depends on a knowledge of the actual cable configurations of the telecommunications facilities and the failure thresholds of equipment interface components. If the threat and hardening measures must be determined precisely, many low level tests and analyses are necessary to avoid low confidence or costly and unnecessary changes to facilities or equipment. Alternate approaches for the general case are possible such as cited above, and involve the specification of cable energy reductions/equipment threshold failure improvements. General acceptance of these latter approaches is not yet a reality and must await further research effort.

III. LIGHTNING

References [17-22] discuss the lightning generation mechanisms in exhaustive detail and describe the important characteristics of the phenomena both as a noise source (the radiation mechanisms, a low-level effect) and as a current source (the conduction mechanism which is a well-known destructive force that requires careful engineering attention to avoid damage).

The lightning radiated field is of little consequence, but it will be briefly described to maintain a consistent and precise frame of reference for the comparison of lightning and EMP. This frame of reference has two parts: The first is the comparison between the radiated fields of the EMP and that of the lightning; the second part compares the energy, voltage, and currents induced by the lightning in system cables and conductors to those induced by the EMP radiated field.

1. LIGHTNING RADIATED FIELD CHARACTERISTICS AND INTERFERENCE STANDARDS

Reference [20] collected and reviewed the literature and measured data on the radiated field from both lightning strokes to ground and strokes or discharges between clouds, as well as discussed the physics for lightning generation mechanisms.

This review shows that the radiated field from the lightning stroke to ground is on the order of 10 V/m or less and has a half-time duration of 40 μs with a rise time of a few microseconds. The intracloud discharge creates a smaller amplitude radiated field of about 0.1V to 1 V/m with a half-time of about 200 μs and a 9 μs rise time. The mathematical form for the pulse waveshape time history is postulated to follow a double exponential, the same shape as that of the EMP threat.

The importance of lightning's radiated field is that it can be a baseline or benchmark interference level. For example, Mil Std 461A, "Electromagnetic Interference Requirements for Equipment, Subsystems and Systems," recognizes the potential of radiated fields to disrupt electronic equipment and provides a set of specifications (RS01-RS03) that can be used for military procurement. It is interesting to note that this standard uses 1 V/m as typical levels for non-susceptibility to interference.

2. LIGHTNING STROKE CHARACTERISTICS, PROTECTION REQUIREMENTS AND STANDARDS

a. General. References [18,21,22] have summarized the engineering data on lightning stroke characteristics in a comprehensive statistical form that is useful to the practicing protection engineer and to those engaged in specifying protection requirements. These protection specifications have evolved over a number of years and are used to test newly manufactured signal line and power equipment for the replacement market and for installation in

new facilities. References [23-29] list some of these standards that are presently in active use by the communications and power industries to specify lightning protection requirements for equipment.

b. Statistical Data on Lightning Strokes. Lightning strokes to earth and direct strokes to wire and cable are the greatest single source of hazardous currents and voltages to facilities, equipment, and personnel. The lightning currents flowing in the conductive discharge paths between the cloud and building and other objects are of such intensity that their magnetic fields and their rates of change cause severe protection problems, not only for nearby objects but for the conductors actually carrying the lightning currents. This protection problem solution requires a knowledge of the stroke crest currents for both aerial and buried cables, the rise and fall times for the lightning currents and the surge voltages associated with these currents. The statistical distribution of these characteristics are well known. Figures 7 and 8 are plots of the Lightning Stroke Crest currents. The median value of crest current is 16 ka and the maximum is 220 ka.

Figures 9 and 10 are statistical plots of the rise and fall time of the lightning stroke surges. The average fall or delay time is 400μs, while the 1 to 99% range is 100 to 2,000 μs. In section II it was shown that the EMP worst-case rise time and half-width time were 10 nanoseconds (ns) and 200 ns, or three orders of magnitude faster. The reader should adjust his thinking to rates of change of voltage and current since this is a significant difference between EMP effects and lightning effects that compromises the protection measures already effective for lightning. (At least at the equipment terminals that actually see the voltage or current surges).

Figure 11 is a composite wave which is used for testing equipment connected to lines that are exposed to possible lightning strokes. It was developed by the telephone and communications industry to provide a standard that encompassed the distributions of amplitudes, and rise and fall times shown in Figures 7 through 10. The standard waveshape is described by two numbers; e.g., 10 X 1000, which indicates that the wave is a mathematical double exponential shape with a rise time of 10 μs and a fall time of 1,000 μs. The amplitudes (1000V in Figure 11) are usually specified in the individual standards; e.g., 1000V in Mil Std 188-100, or in the equipment purchase orders.

3. THE LIGHTNING HAZARD AND PROTECTION AGAINST IT FOR FACILITY EQUIPMENTS AND COMPONENTS

The lightning surge amplitude specification, its energy content, and its application embodies several basic principles. In the specific case of Figure 11, the amplitude specification (for the lightning hazard) bears a significant relationship to the breakdown voltage characteristics of the carbon block and gas tube protectors normally used on signal lines. That is, the signal line equipment is tested to the worst-case transient (voltage and energy) shown in Figure 11, while the protector is designed and manufactured to protect

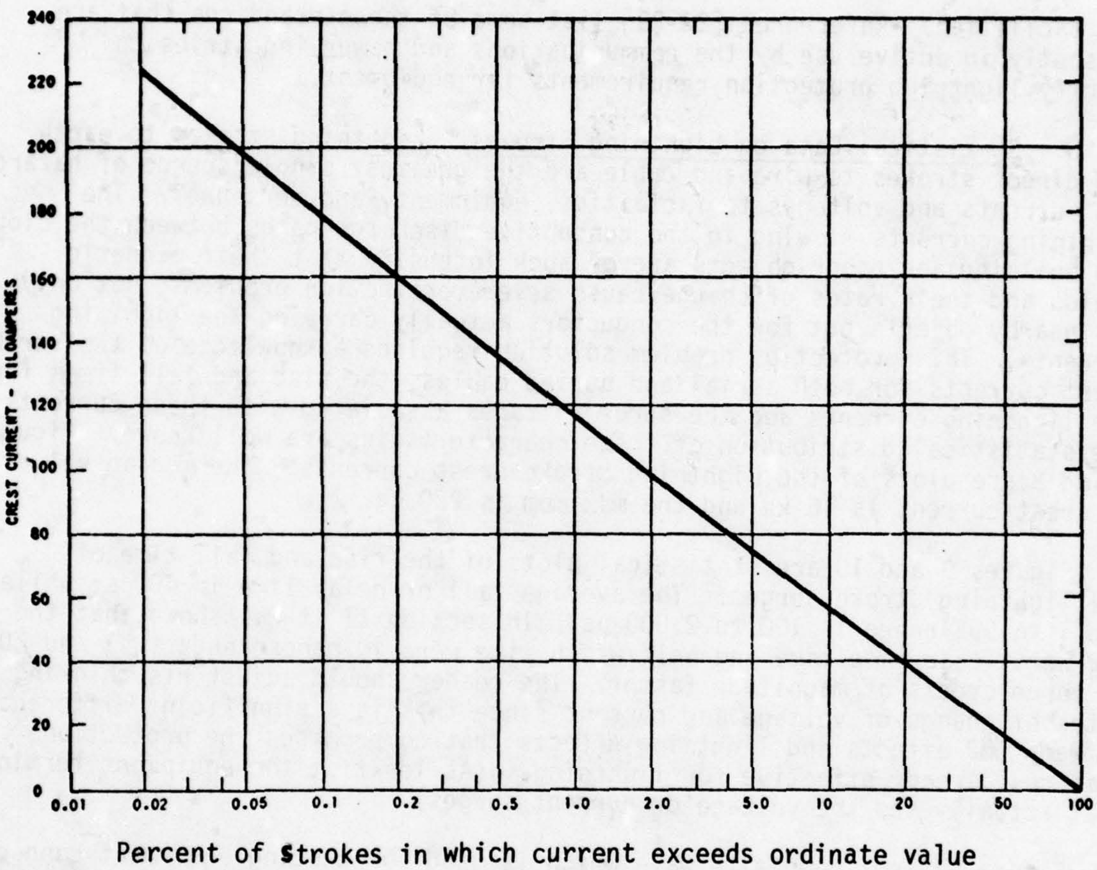
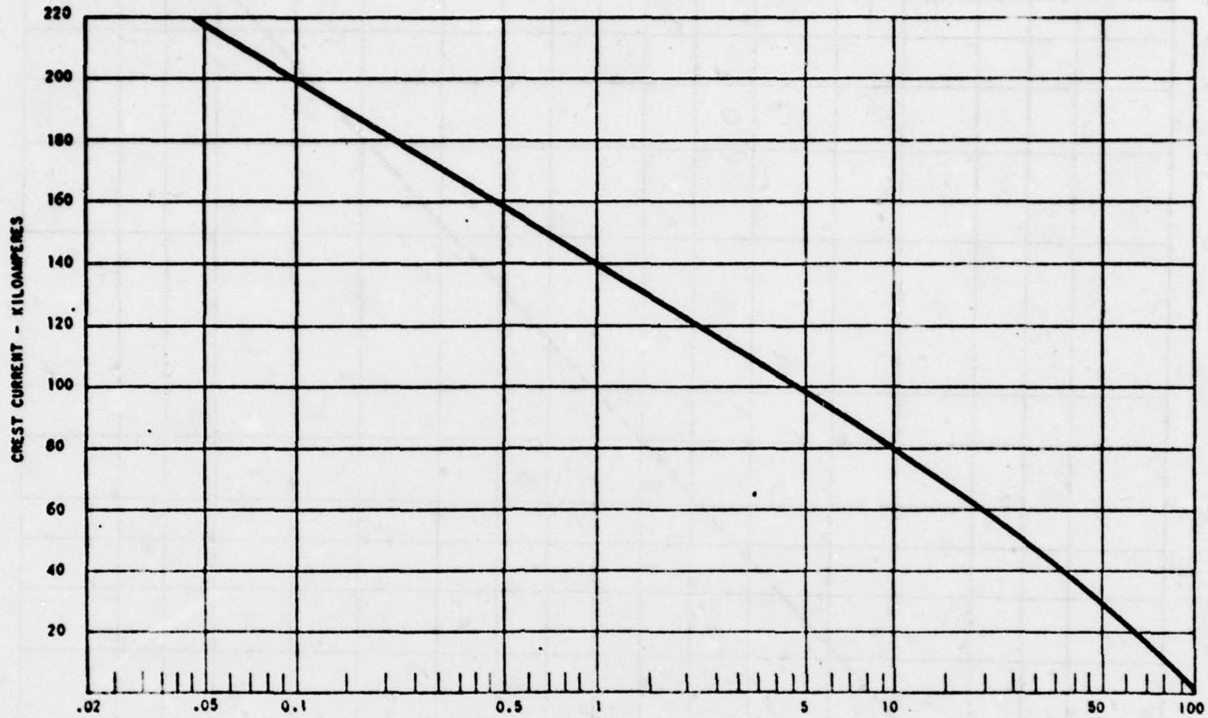


Figure 7. Distribution of Lightning Stroke Crest Currents to Aerial Structures [21,22]



Percent of strokes in which current exceeds ordinate value

Figure 8. Distribution of Lightning Stroke Crest Currents to Buried Structures [21,22]

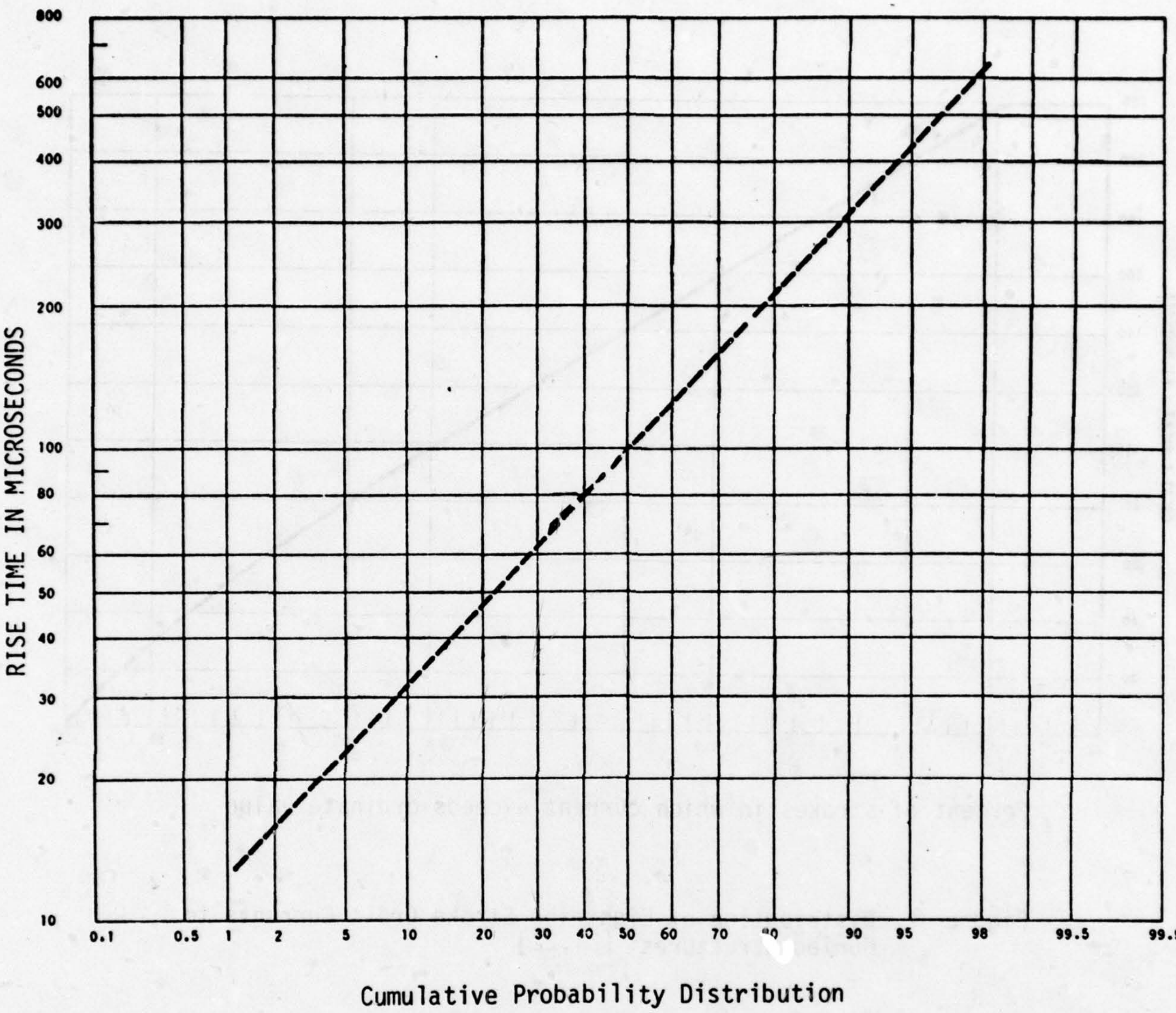


Figure 9. Distribution of Rise Times of Lightning Surges in Telephone Cable Pairs [21,22]

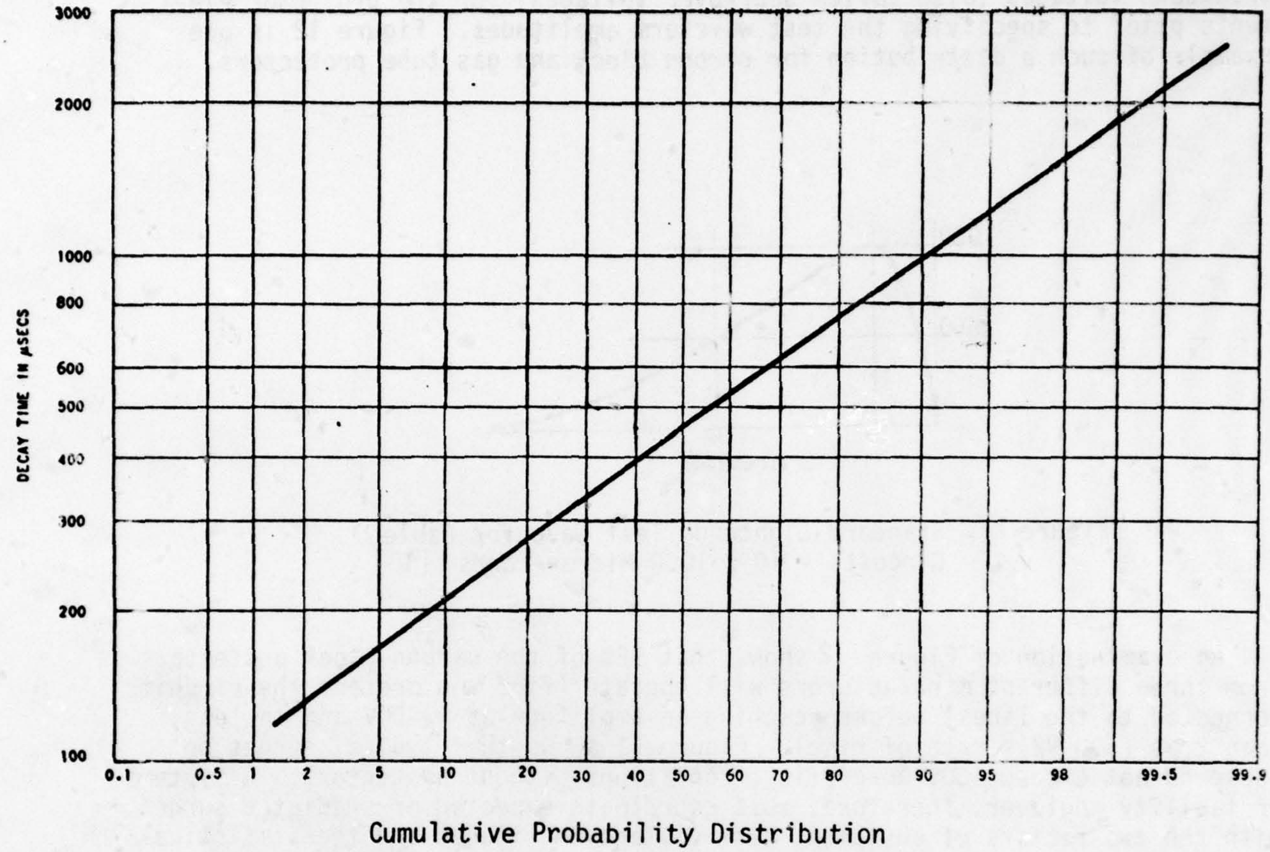


Figure 10. Distribution of Decay Times of Lightning Surges in Telephone Cable Pairs [21,22]

against all values of voltage and energy that exceed the test waveform. It is very important, therefore, to know the statistical distribution of the breakdown voltages (also called sparkover voltages) for the protector elements prior to specifying the test waveform amplitudes. Figure 12 is one example of such a distribution for carbon block and gas tube protectors.

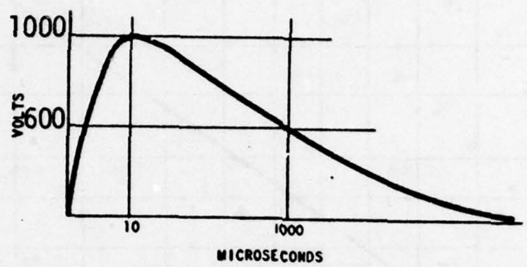


Figure 11. Standard Lightning Test Wave for Cable Circuits - 10 X 1000 Microseconds [18]

An examination of Figure 12 shows that 98% of the carbon block protectors from three different manufacturers will operate (fire and protect the circuits connected to the lines) before reaching an amplitude of 1,000V and in less than 2 μs (500 V/μs rate of rise). Figure 13 shows that typical surges on cable do not exceed 600V under field conditions without protectors. A systems or facility engineer, therefore, must coordinate expected or predicted surges with the two factors of equipment test voltage amplitudes and the statistical upper limit breakdown voltage for the facility or equipment rack protectors. This coordination has been accomplished for the lightning effects on power and signal lines using the various characteristics of protectors such as carbon blocks, gas tubes, and primary/secondary lightning arrestors, coupled with transient insulation voltage tests of the equipment connected to such lines. It is crucial to note that the energy in these lightning test waveforms exceeds that of any EMP waveform measured in DCA field tests or predicted at any equipment interface or terminals connected to signal lines or power lines.

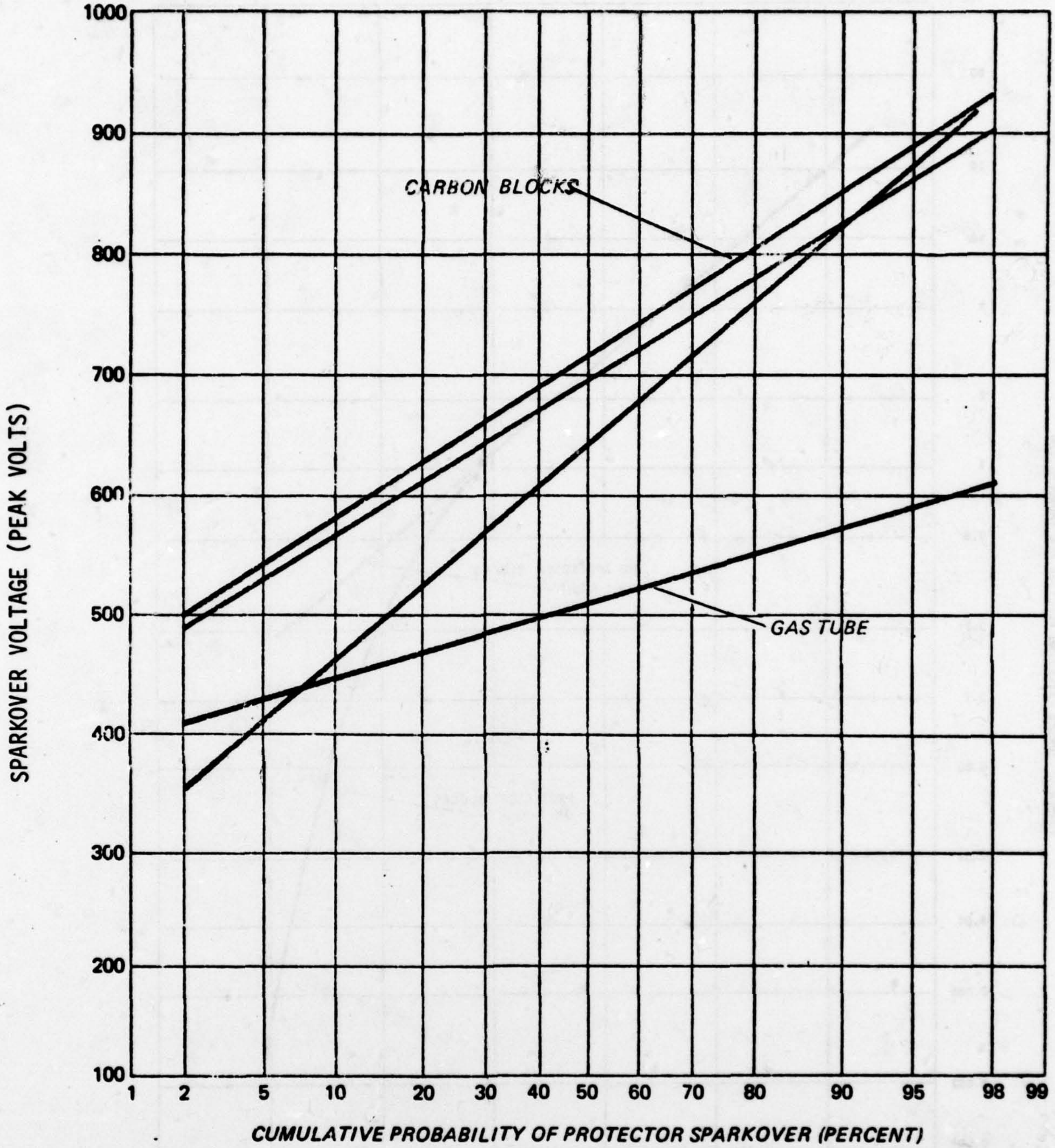


Figure 12. Initial Surge Sparkover Characteristics of Carbon-Block and Gas-Tube Protectors [21,22]

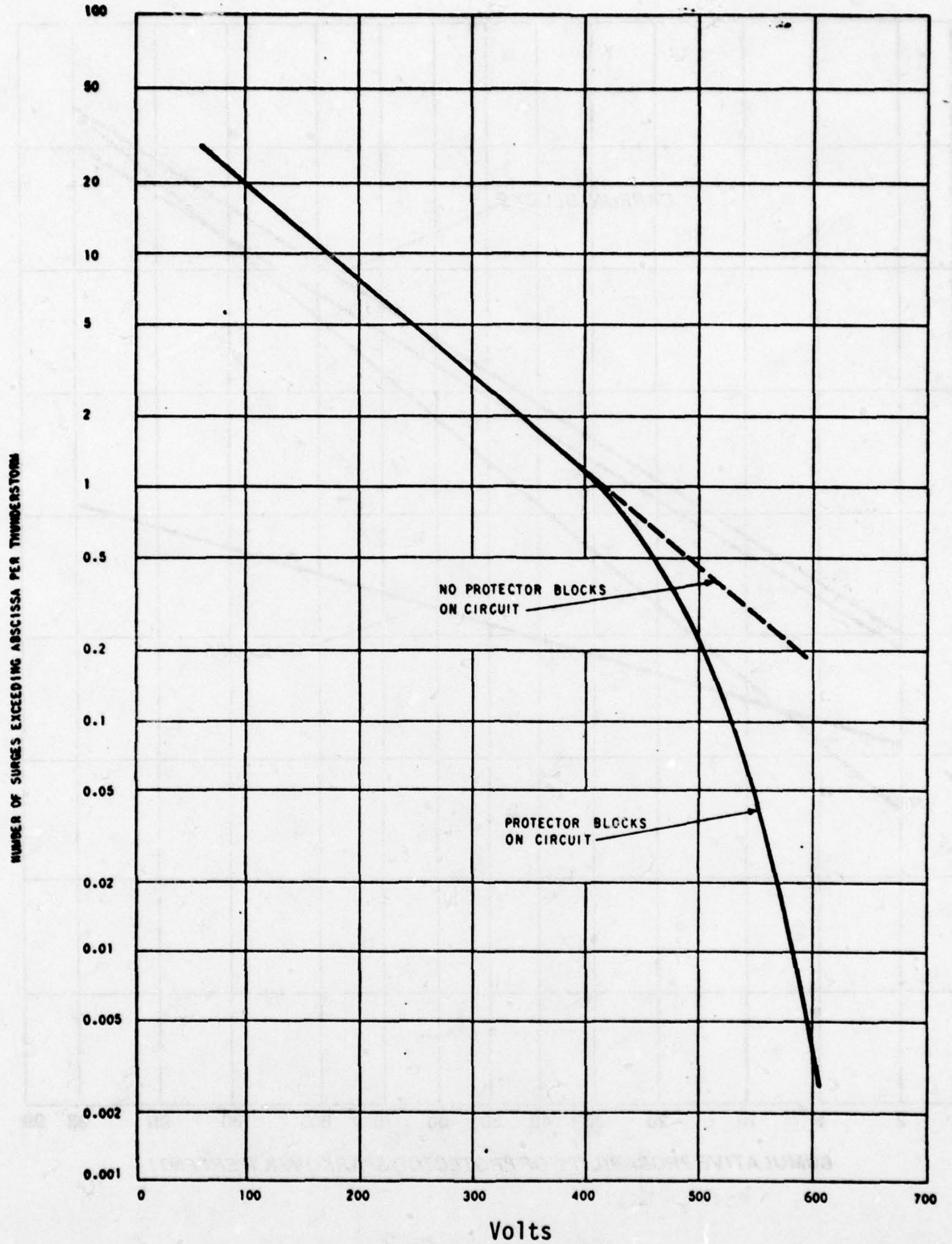


Figure 13. Surge Voltage Distribution on Buried and Aerial Cable [21,22]

A value for the lightning test waveform energy will be required for later comparison to EMP component damage failure levels; therefore, a simple calculation is essential to form a first order numerical basis for these EMP, lightning, and power transient energy comparisons. This energy value for the lightning hazard case is 3.13 joules (J) and was calculated using a two-segment triangular straight line approximation of waveform given in Figure 11 and integrating the result as follows:

$$E = \int_0^{t_1} \frac{V(t)^2}{Z}\, dt + \int_{t_1}^{t_2} \frac{V(t)^2}{Z}\, dt$$

$$= .03 \text{ joules} + 3.1 \text{ joules} = 3.13 \text{ joules}$$

where

E is in joules

Z is common mode line impedance, a typical value of 100 ohms was used

t is time, $t_1 = 10\ \mu s$, $t_2 = 1{,}000\ \mu s$

V(t) - the voltage ramps for the waveform approximation at 1,000V.

The details of power line lightning surges have notbeen considered here since most telecommunication facilities have standby power to preclude outage problems due to power loss or damage from lightning or any other cause. The magnitude of these surges, however, is in the range of 200kV to 4MV at currents up to 220 ka with energies up to three joules with ringing frequencies up to 1 MHz. Reference [30] has sufficient bibliography and data for the interested reader that can be used to study and catalog these surge magnitudes for power lines in greater detail.

IV. POWER LINE TRANSIENT HAZARDS

This discussion is concerned with the day-to-day transient voltages and energies produced on AC power mains operating at low voltages. The primary objective is to present some engineering data that indicates the magnitude of these transients as seen by typical equipment and secondly to provide a frame of reference for comparison to the transients produced by EMP. The normal environmental voltage surges and their energy content as seen at the equipment terminals involved is a point of departure for starting EMP standards efforts.

The treatment here is brief and incomplete for two reasons: (1) the available data on surge magnitudes, energy, spectral content, and frequency of occurrence is very limited, and (2) the electrical surge environment is not well defined in that there are no recognized standards concerning the surge withstanding requirements/capability of many types of equipment. In fact, the available references suggest that the manufacturers of load equipment are primarily interested and concerned with overvoltage problems directly related to the operation of their own systems (self generated voltages and their effect on the manufactured equipment reliability).

Destructive transient overvoltages may arise from several sources; namely, (1) surges on primary distribution circuits from switching operations, arcing faults, and their transfer by magnetic or capacitive coupling into secondary circuits, (2) feedback disturbances caused by transients generated within load circuits which then enter adjacent loads, and (3) induction in low-voltage circuits through mutual coupling with high-voltage disturbed sources.

Useful references are [30-36]. References [30-34] provide an extensive bibliography and many of the analytical magnitudes once system parameters are known. Reference [35] is an IEEE working group bibliography on surge voltages in low voltage AC power circuits while reference [36] is a valuable field study by the General Electric Company, which provided a data base of actual measured surge voltages at 400 locations in 20 cities on low voltage power circuits. Table III is reproduced from that reference and shows that the measured surges vary from a low of 300 volts peak to as high as 5600 volts peak. The tabulated durations are from 5 usec to 30 usec. These time durations and magnitudes are much greater than expected for 120 VAC mains when compared to insulation test voltages of some load equipments (1000 volts).

The Table II magnitudes and durations are probably not atypical and some analytical examples from references [31-34] support these values and also include energy levels of about 50 mJ or greater with a frequency range from about 600 Hz to 1.5 MHz.

TABLE II. DETAILED ANALYSIS OF RECORDED SURGES [36]

House	Most Severe Surge Type*	Crest (volts)	Duration (μs or cycles)	Most Frequent Surge Type*	Crest (volts)	Duration (μs or cycles)	Average Surges per Hour	Remarks
1	A-1.5	700	10 μs	A-1.5	300	10 μs	0.07	
2	A-2.0	750	20 μs	A-2.0	500	20 μs	0.14	fluorescent light switching
3	B-0.5	600	1 cycle	B-0.5	300	1 cycle	0.05	
4	B-0.5	400	2 cycles	B-0.5	300	2 cycles	0.2	
5	C	640	5 μs	too few to show typical			10 total	
6	B-0.3	400	1 cycle	B-0.3	250	1 cycle	0.01	
7	B-1	1800	1 cycle	B-1.0	800	1 cycle	0.03	lightning storm
8	C	1200	10 μs	B-0.5	300	4 cycles	0.1	
9	B-0.25	1500	1 cycle	same as most severe			0.2	oil burner
10	B-0.25	2500	1 cycle	B-0.25	2000	1 cycle	0.4	oil burner
11	B-0.2	1500	1 cycle	same as most severe			0.15	water pump
12	B-0.2	1700	1 cycle	B-0.2	1400	1 cycle	0.06	oil burner
13	B-0.1	350	1 cycle	too few to show typical			4 total	house next to 12
14	C	800	15 μs	—	—	—	1 total	lightning
15	B-0.25	800	3 cycles	B-0.25	600	3 cycles	0.05	rural area
16	B-0.15	400	15 μs	B-0.13	200	30 μs	0.4	surges
Street pole	B-0.5	5600	4 cycles	B-0.3	1000	1 cycle	0.1	lightning stroke nearby
Hospital	C	2700	9 μs	C	900	5 μs	0.1	lightning storm
Hospital	B-0.3	1100	1 cycle	too few to show typical			4 total	
Department store	B-0.5	300	1 cycle	B-0.5	300	1 cycle	0.5	
Street pole	B-0.2	1400	4 cycles	B-0.2	600	4 cycles	0.07	lightning storm

* A—long oscillation; B—damped oscillation; C—unidirectional. Number shows frequency in megahertz.

A number of standards are in use by equipment procurement specialists; e.g., REA, PE 60, IEEE 472-1974 and Mil Std 461A, CS06. A brief comparison of the latter two specifications to the surge data of Table III is interesting and enlightning. The CS06 specification requires a maximum of 100V at 100 kHz test for any equipment terminals connected to DC and AC power lines, while the IEEE specification requires a test of 2500 volts at 1.25 MHz. Obviously, neither specification is totally adequate for every task as stated earlier, but military equipment procured using Mil Std 461 appears to offer much less protection for the same transient environment.

The higher voltage AC power lines are also subject to substantial transients for the same reasons cited earlier. A larger data base is available for this case but was not assessed. Some insights can be gained from the previous discussion and a study of references [30-34].

In conclusion, non-uniformity exists between the various standards for stress testing and the actual values of measured stress in the normal environment. The justification for these differences is not known. The result may be higher failure rates for some equipment and is dependent on the nature of the various loads on the system power. The more subtle problem is one of maintaining the status quo since the facility power transient surges can be altered as new equipment is installed in the various facilities. In general, the facility engineer at the present time must decide whether to add filters,

protection devices or specify higher surge test voltages for any new equipment based on either direct measurement of surges or by some statistical procedure based on failure rates or simply experience. Briefly, however, for the sake of later comparison to the expected EMP surges the range of AC power transient surges expected at the equipment connections to the AC power will be selected as 100 volts to 2500 volts (based on the Mil Std 461 and IEEE specifications) at frequencies from 60 Hz to 1.25 MHz. The test energy levels are chosen as ranging from a low of about 60 mJ for low voltage mains up to a maximum of about 2 joules for the high voltage mains.

V. SUMMARY OF FINDINGS AND CONCLUSIONS

The basic data for the comparison among EMP, lightning and power line transients has been presented in Sections II, III, and IV. These data are tabulated in Table II.

The data in Table IIIshow that:

a. Lightning and power line transients can contain larger amounts of energy than any EMP coupling situation.

b. The maximum voltage stress expected at equipment interfaces from lightning/power transients equal or exceed those for EMP.

c. The high frequency effects/high rates of rise predominate for EMP compared to lightning and power line transients and covers the range from about 1 MHz to 20 MHz; i.e., range of about 10 to 500 ns for rise time.

The energy stress levels of lightning and power transients exceed those of EMP for many situations. The development of Federal standard/specifications for EMP protection must take cognizance of the protective measures that are applied to protect equipment from lightning and power transients. The technical feasibility of protecting equipment against EMP damage is not an issue. The primary EMP protection issues concern economic practicability and selection of the most economical protection measures from a range of alternatives.

Approaches to protection of equipment against EMP damage include:

a. Shielding of buildings/rooms and application of energy suppression techniques on all types of cables which penetrate the shield,

b. Providing EMP protection solely at the equipment/black box level, and

c. A combination of energy transient protective measures which exploits to the maximum extent the protection techniques that must be applied to facilities/equipment to operate effectively in the lightning, power transient, electromagnetic compatability, TEMPEST and similar environments.

There are significant differences between Industrial and Military Standards which define the power transient environment and provisions for stress testing. Additional surge measurement information is needed to determine the optimal approach to power transient protection.

TABLE III. TRANSIENT COMPARISON CHART FOR EMP, LIGHTNING AND POWER (ESTIMATED)

EQUIPMENT INTERFACE	LIGHTNING			EMP			POWER LINE TRANSIENT		
	Energy	Freq.	Volt/ Current	Energy	Freq.	Volt/ Current	Energy	Freq.	Volt/ Current
Penetrators	<3 joules (1)	≤1 MHz	200 kV to 4 MV up to 220 k a	.2 to 2.0 joules	.1-20 MHz	200 kV to 1 MV @ 3 k a (2)	2.0 joules	60 Hz to 1.25 MHz (3)	300-5600V (7)
Intra-site	<3 joules	≤1 MHz	600-1000V	≤.01	.1-20 MHz (4)	≤1300 V & 10 Amperes (5)	.2 joules	60 Hz to 1.25 MHz (3)	100-2500V (3)
Penetrator/Intra-site Mutual Coupling	NOT ESTIMATED			≤.2	.1-20 MHz	≤60 Amperes (6)	.2 joules	60 Hz to 1.25 MHz (3)	100-2500 V (3)

(1) Energy with protectors installed and not operating.
(2) Reference [9].
(3) Upper Limits for Power Line Transients from Reference [28].
(4),(6) Upper Limit from Reference [2] and [7].
(5) Upper Limits from Reference [14] with Connection to Penetrators
(7) Reference [36]

REFERENCES

[1] DNA 2114H-1, Defense Nuclear Agency EMP (Electromagnetic Pulse Handbook), November 1971.

[2] <u>EMP Engineering and Design Principles</u>, Bell Laboratories, 1975.

[3] Defense Civil Preparedness Agency TR 61-D, "EMP and Electric Power Systems," July 1973.

[4] Defense Civil Preparedness Agency CPG 2-14A, "DCPA Attack Environment Manual, Chapter 4," June 1973.

[5] Office of Civil Defense TR 61A, "EMP Protection for Emergency Operating Centers," May 1971.

[6] NSWC/WOL/TR 75-193, "EMP Design Guidelines for Naval Ship Systems," August 1975.

[7] MITRE Corp. Final Report M74-220, V1 to V5, "Safeguard Communications Test Analysis Program," L. Bickmore and S. Watford, August 1974.

[8] DNA 4162T, "Probability Distribution of CW Induced Currents on Randomly Oriented Sub-Resonant Loops and Wires," Graham and Mo, May 1976.

[9] DNA 2114H-1, DNA EMP (Electromagnetic Pulse Handbook, Chapter 11, November 1971.

[10] Stanford Research Institute Final Report, SRI 6-4294, "HEMP Hardness Assessment of 16 CONUS/Canada AECo AUTOVON Switch Centers," A. Whitson, G. August, May 1976.

[11] Stanford Research Institute Final Report, SRI 4-4470, "HEMP Characteristics of the AECo AUTOVON Switch," J. Lomax, B. Tupper, May 1974.

[12] Stanford Research Institute, Technical Note, SRI-20D, "AECo AUTOVON Switch Response Similarity," A. Whitson, E. Clark, July 1975.

[13] Stanford Research Institute, Final Report, SRI 4-4579, "HEMP Assessment for an AUTOVON Switch Center and GTF Radio Facility at Polk City, Florida," A. Whitson, G. August, June 1974.

[14] D180-20314-1, "Intrasite Cabling Program for Defense Communications Engineering Center," December 1976.

[15] DNA 3339F, "Facility Response Predictions," W. Cooley, January 1974.

[16] Boeing Co., DNA 3339F, "Facility Response Predictions," Energy Graphs, W. Cooley, January 1974.

[17] Bell System, "Electrical Protection Principles, Section 876-100-100, Issue 7, Bell System Practices," November 1972.

[18] Bell System, "Protection Practices, Exchange Aerial Cable Protection - Lightning, Section 876-400-100, Issue 1, Bell System Practices," January 1947.

[19] H. M. Trueblood and E. D. Sunde, "Lightning Current Observations in Buried Cable," BSTJ, April 1949.

[20] DASA 2299, "The Thunderstorm as a Source of Atmospheric Noise at Frequencies Between 1 and 100 KHz," E. Pierce, June 1969.

[21] "Communications Protectors, System Requirements and Performance Evaluation," D. Bodle, Joslyn Electronic Systems, 1973.

[22] "Electrical Protection Guide for Land Based Radio Facilities," D. Bodle, Joslyn Electronic Systems, 1971.

[23] Mil Std 188-100, Page 30, Circuit Protection.

[24] Mil Std 188-114, Page 19, Circuit Protection.

[25] Mil Std 461A, Notice 4, Page 19-20, Limits for RS01, RS02, RS03 (Radiated Susceptibility).

[26] Mil Std 461A, Notice 4, Page 17-18, Limits for Page 62, Figure 8, Page 60 for CS01. Conducted Susceptibility Requirements for DC Power Lines and AC Power Lines.

[27] Federal Std 1020 and 1030 for Digital Interfaces.

[28] IEEE Std 472-1974/ANSI Std C37.90a, 1974 (Test Surge Requirement of 2.5 kV, 1.25 MHz Damped Sine Wave for Power Lines).

[29] REA Bulletin 345-30 and REA Specification PE-60 for Trunk Carrier Multiplex Equipment, Surge Tests of Paragraph 13, Page 10-13.

[30] Electrical Transients in Power Systems, Chapter 12, "Protection of Systems and Equipment Against Transient Overvoltages," A. Greenwood, Wiley-Interscience, 1971.

[31] Electrical Transients in Power Systems, Page 282, A. Greenwood, Wiley-Interscience, 1971.

[32] Electrical Transients in Power Systems, pp 312-315, A. Greenwood, Wiley-Interscience, 1971.

[33] Electrical Transients in Power Systems, Page 338, A. Greenwood, Wiley-Interscience, 1971.

[34] Electrical Transients in Power Systems, Page 293, A. Greenwood, Wiley-Interscience, 1971.

[35] IEEE Committee Report, "Bibliography on Surge Voltages in AC Power Circuits Rated 600 Volts or Less," IEEE Trans., PAS 89, July/August 1970.

[36] F. D. Martzloff, "Surge Voltages in Residential and Industrial Power Circuits," IEEE Trans. PAS, July/August 1970.